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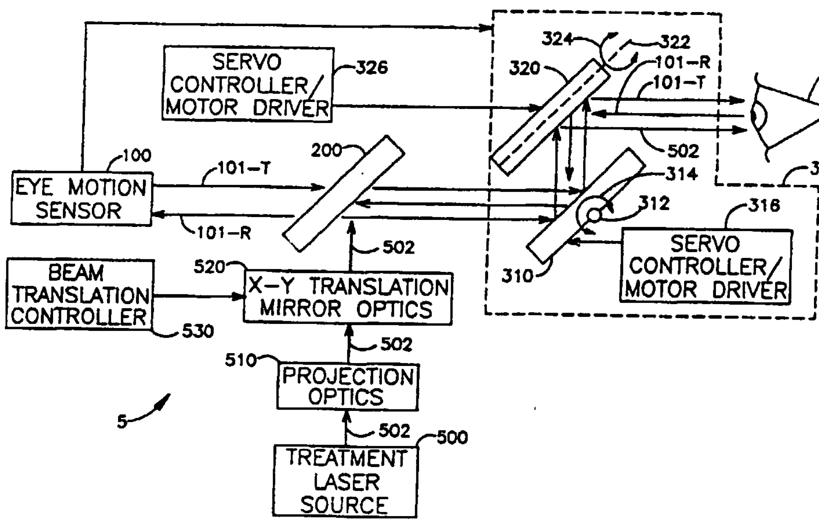


**(57) Abstract**

A surface treatment laser beam delivery and tracking system. The laser (500) generates laser light (502) along a path at an energy level suitable for treating a surface. An optical translator (520) shifts the path onto a resulting beam path. An optical angle adjuster (310, 316, 320, 326) changes the angle of the resulting beam path relative to the original path such that the laser light is incident on the surface to be treated. A motion sensor (100) transmits light energy (101-T) to the surface and receives reflected light energy (101-R) from the surface via the optical angle adjuster. The light energy travels on a parallel path to the shifted beam through the optical angle adjuster. The motion sensor detects movement of the surface relative to the original path and generates error control signals indicative of the movement. The optical angle adjuster responds to the error control signals to change the angle of the resulting beam path.

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# LASER BEAM DELIVERY AND EYE TRACKING SYSTEM

This patent application is copending with related patent applications entitled "Eye Movement Sensing Method and System" and "Laser Sculpting System and Method" filed on the same date and owned by a common assignee as subject patent application. The disclosures of these applications are incorporated herein by reference.

## Field of the Invention

The invention relates generally to laser systems, and more particularly to a laser system used to erode a moving surface such as an eye's corneal tissue.

## Background of the Invention

Use of lasers to erode all or a portion of a workpiece's surface is known in the art. In the field of ophthalmic medicine, photorefractive keratectomy (PRK) is a procedure for laser correction of focusing deficiencies of the eye by modification of corneal curvature. PRK s distinct from the use of laser-based devices for more traditional ophthalmic surgical purposes, such as tissue cutting or thermal coagulation. PRK is generally accomplished by use of a 193 nanometer wavelength excimer laser beam that ablates away the workpiece, i.e., corneal tissue, in a photo decomposition process. Most clinical work to this point has been done with a laser operating at a fluence level of 120-195 mJ/cm$^2$ and a pulse-repetition rate of approximately 5-10 Hz. The procedure has been referred to as "corneal sculpting."

Before sculpting of the cornea takes place, the epithelium or outer layer of the cornea is mechanically removed to expose Bowman's membrane on the anterior surface of the stroma. At this point, laser ablation at Bowman's layer can begin. An

excimer laser beam is preferred for this procedure. The beam may be variably masked during the ablation to remove corneal tissue to varying depths as necessary for recontouring the anterior stroma. Afterward, the epithelium rapidly regrows and resurfaces the contoured area, resulting in an optically correct (or much more nearly so) cornea. In some cases, a surface flap of the cornea is folded aside and the exposed surface of the cornea's stroma is ablated to the desired surface shape with the surface flap then being replaced.

Phototherapeutic keratectomy (PTK) is a procedure involving equipment functionally identical to the equipment required for PRK. The PTK procedure differs from PRK in that rather than reshaping the cornea, PTK uses the aforementioned excimer laser to treat pathological superficial corneal dystrophies, which might otherwise require corneal transplants.

In both of these procedures, surgical errors due to application of the treatment laser during unwanted eye movement can degrade the refractive outcome of the surgery. The eye movement or eye positioning is critical since the treatment laser is centered on the patient's theoretical visual axis which, practically speaking, is approximately the center of the patient's pupil. However, this visual axis is difficult to determine due in part to residual eye movement and involuntary eye movement known as saccadic eye movement. Saccadic eye movement is high-speed movement (i.e., of very short duration, 10-20 milliseconds, and typically up to 1° of eye rotation) inherent in human vision and is used to provide dynamic scene to the retina. Saccadic eye movement, while being small in amplitude, varies greatly from patient to patient due to psychological effects, body

chemistry, surgical lighting conditions, etc. Thus, even though a surgeon may be able to recognize some eye movement and can typically inhibit/restart a treatment laser by operation of a manual switch, the surgeon's reaction time is not fast enough to move the treatment laser in correspondence with eye movement.

## Summary of the Invention

Accordingly, it is an object of the present invention to provide a laser beam delivery and eye tracking method and system that is used in conjunction with a laser system capable of eroding a surface.

Another object of the present invention is to provide a system for delivering a treatment laser to a surface and for automatically redirecting the treatment laser to compensate for movement of the surface.

Still another object of the present invention is to provide a system for delivering a corneal ablating laser beam to the surface of an eye in a specific pattern about the optical center of the eye, and for automatically redirecting the corneal ablating laser beam to compensate for eye movement such that the resulting ablating pattern is the same regardless of eye movement.

Yet another object of the present invention is to provide a laser beam delivery and eye tracking system for use with an ophthalmic treatment laser where the tracking operation detects eye movement in a non-intrusive fashion.

A further object of the present invention is to provide a laser beam delivery and eye tracking system for automatically delivering and maintaining a corneal ablating laser beam with respect to the geometric center of an eye's pupil or a doctor defined offset

from the center of the eye's pupil. A special object of this invention is the use of the laser pulses which are distributed in a pattern of discrete ablations to shape objects other than for corneal ablating.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

In accordance with the present invention, an eye treatment laser beam delivery and eye tracking system is provided. A treatment laser and its projection optics generate laser light along an original beam path (i.e., the optical axis of the system) at an energy level suitable for treating the eye. An optical translator shifts the original beam path in accordance with a specific scanning pattern so that the original beam is shifted onto a resulting beam path that is parallel to the original beam path. An optical angle adjuster changes the resulting beam path's angle relative to the original beam path such that the laser light is incident on the eye.

An eye movement sensor detects measurable amounts of movement of the eye relative to the system's optical axis and then generates error control signals indicative of the movement. The eye movement sensor includes: 1) a light source for generating light energy that is non-damaging with respect to the eye, 2) an optical delivery arrangement for delivering the light energy on a delivery light path to the optical angle adjuster in a parallel relationship with the resulting beam path of the treatment laser, and 3) an optical receiving arrangement. The parallel relationship between the eye movement sensor's delivery light path and the treatment laser's resulting beam path is maintained by the optical angle adjuster. In this way, the treatment laser light and

the eye movement sensor's light energy are incident on the eye in their parallel relationship.

A portion of the eye movement sensor's light energy is reflected from the eye as reflected energy traveling on a reflected light path back through the optical angle adjuster. The optical receiving arrangement detects the reflected energy and generates the error control signals based on the reflected energy. The optical angle adjuster is responsive to the error control signals to change the treatment laser's resulting beam path and the eye movement sensor's delivery light path in correspondence with one another. In this way, the beam originating from the treatment laser and the light energy originating from the eye movement sensor track along with the eye's movement.

In carrying out this technique, the pattern constitutes overlapping but not coaxial locations for ablation to occur with each pulse removing a microvolume of material by ablation or erosion. For different depths, a pattern is repeated over those areas where increased ablation is needed. The laser pulses are usually at a certain pulse repetition rate. The subsequent pulses in a sequence are spaced at least one pulse beam width from the previous pulse and at a distance the ablated particles will not substantially interfere with the subsequent pulse. In order to maximize the speed of the ablation, the subsequent pulse is spaced sufficiently close to enable the beam to be moved to the successive location within the time of the pulse repetition. The ablation is carried out on an object until a desired specific shape is achieved.

This technique is fundamentally new and may be used on objects other than corneas.

Brief Description of the Drawings

FIG. 1 is a block diagram of a laser beam delivery and eye tracking system in accordance with the present invention as it would be used in conjunction with an ophthalmic treatment laser;

FIG. 2 is a sectional view of the projection optics used with the ophthalmic treatment laser embodiment of the laser beam delivery portion of the present invention;

FIG. 3 illustrates diagrammatically an optical arrangement of mirrors used to produce translational shifts in a light beam along one axis;

FIG. 4 is a block diagram of the servo controller/motor driver circuitry used in the ophthalmic treatment laser embodiment of the present invention; and

FIG. 5 is a block diagram of a preferred embodiment eye movement sensor used in the ophthalmic treatment laser embodiment of the present invention.

Detailed Description of the Invention

Referring now to the drawings, and more particularly to FIG. 1, a block diagram is shown of a laser beam delivery and eye tracking system referenced generally by the numeral 5. The laser beam delivery portion of system 5 includes treatment laser source 500, projection optics 510, X-Y translation mirror optics 520, beam translation controller 530, dichroic beamsplitter 200, and beam angle adjustment mirror optics 300. By way of example, it will be assumed that treatment laser 500 is a 193 nanometer wavelength excimer laser used in an ophthalmic PRK (or PTK) procedure performed on a movable workpiece. e.g., eye 10. However, it is to be understood that the method and system of the present invention will apply equally

as well to movable workpieces other than an eye, and further to other wavelength surface treatment or surface eroding lasers. The laser pulses are distributed as shots over the area to be ablated or eroded, preferably in a distributed sequence. A single laser pulse of sufficient power to cause ablation creates a micro cloud of ablated particles which interferes with the next laser pulse if located in the same or immediate point. To avoid this interference, the next laser pulse is spatially distributed to a next point of erosion or ablation that is located a sufficient distance so as to avoid the cloud of ablated particles. Once the cloud is dissipated, another laser pulse is made adjacent the area prior eroded so that after the pattern of shots is completed the cumulative shots fill in and complete said pattern so that the desired shape of the object or cornea is achieved.

In operation of the beam delivery portion of system 5, laser source 500 produces laser beam 502 which is incident upon projection optics 510. Projection optics 510 adjusts the diameter and distance to focus of beam 502 depending on the requirements of the particular procedure being performed. For the illustrative example of an excimer laser used in the PRK or PTK procedure, projection optics 510 includes planar concave lens 512, and fixed focus lenses 514 and 516 as shown in the sectional view of FIG. 2. Lenses 512 and 514 act together to form an A-focal telescope that expands the diameter of beam 502. Fixed focus lens 516 focuses the expanded beam 502 at the workpiece, i.e., eye 10, and provides sufficient depth, indicated by arrow 518, in the plane of focus of lens 516. This provides flexibility in the placement of projection optics 510 relative to the

surface of the workpiece. An alternative implementation is to eliminate lens 514 when less flexibility can be tolerated.

After exiting projection optics 510, beam 502 impinges on X-Y translation mirror optics 520 where beam 502 is translated or shifted independently along each of two orthogonal translation axes as governed by beam translation controller 530. Controller 530 is typically a processor programmed with a predetermined set of two-dimensional translations or shifts of beam 502 depending on the particular ophthalmic procedure being performed. For the illustrative example of the excimer laser used in a PRK or PTK procedure, controller 530 may be programmed in accordance with the aforementioned copending patent application entitled "Laser Sculpting System and Method". The programmed shifts of beam 502 are implemented by X-Y translation mirror optics 520.

Each X and Y axis of translation is independently controlled by a translating mirror. As shown diagrammatically in FIG. 3, the Y-translation operation of X-Y translation mirror optics 520 is implemented using translating mirror 522. Translating mirror 522 is movable between the position shown and the position indicated by dotted line 526. Movement of translating mirror 522 is such that the angle of the output beam with respect to the input beam remains constant. Such movement is brought about by translation mirror motor and control 525 driven by inputs received from beam translation controller 530. By way of example, motor and control 525 can be realized with a motor from Trilogy Systems Corporation (e.g., model T050) and a control board from Delta Tau Systems (e.g., model 400-602276 PMAC).

With translating mirror 522 positioned as shown,

beam 502 travels the path traced by solid line 528a. With translating mirror 522 positioned along dotted line 526, beam 502 travels the path traced by dotted line 528b. A similar translating mirror (not shown) would be used for the X-translation operation. The X-translation operation is accomplished in the same fashion but is orthogonal to the Y-translation. The X-translation may be implemented prior or subsequent to the Y-translation operation.

The eye tracking portion of system 5 includes eye movement sensor 100, dichroic beamsplitter 200 and beam angle adjustment mirror optics 300. Sensor 100 determines the amount of eye movement and uses same to adjust mirrors 310 and 320 to track along with such eye movement. To do this, sensor 100 first transmits light energy 101-T which has been selected to transmit through dichroic beamsplitter 200. At the same time, after undergoing beam translation in accordance with the particular treatment procedure, beam 502 impinges on dichroic beamsplitter 200 which has been selected to reflect beam 502 (e.g., 193 nanometer wavelength laser beam) to beam angle adjustment mirror optics 300.

Light energy 101-T is aligned such that it is parallel to beam 502 as it impinges on beam angle adjustment mirror optics 300. It is to be understood that the term "parallel" as used herein includes the possibility that light energy 101-T and beam 502 can be coincident or collinear. Both light energy 101-T and beam 502 are adjusted in correspondence with one another by optics 300. Accordingly, light energy 101-T and beam 502 retain their parallel relationship when they are incident on eye 10. Since X-Y translation mirror optics 520 shifts the position of beam 502 in translation independently of optics 300, the parallel

relationship between beam 502 and light energy 101-T is maintained throughout the particular ophthalmic procedure.

Beam angle adjustment mirror optics consists of independently rotating mirrors 310 and 320. Mirror 310 is rotatable about axis 312 as indicated by arrow 314 while mirror 320 is rotatable about axis 322 as indicated by arrow 324. Axes 312 and 322 are orthogonal to one another. In this way, mirror 310 is capable of sweeping light energy 101-T and beam 502 in a first plane (e.g., elevation) while mirror 320 is capable of independently sweeping light energy 101-T and beam 502 in a second plane (e.g., azimuth) that is perpendicular to the first plane. Upon exiting beam angle adjustment mirror optics 300, light energy 101-T and beam 502 impinge on eye 10.

Movement of mirrors 310 and 320 is typically accomplished with servo controller/motor drivers 316 and 326, respectively. FIG. 4 is a block diagram of a preferred embodiment servo controller/motor driver 316 used for the illustrative PRK/PTK treatment example. (The same structure is used for servo controller/motor driver 326.) In general, drivers 316 and 326 must be able to react quickly when the measured error from eye movement sensor 100 is large, and further must provide very high gain from low frequencies (DC) to about 100 radians per second to virtually eliminate both steady state and transient error.

More specifically, eye movement sensor 100 provides a measure of the error between the center of the pupil (or an offset from the center of the pupil that the doctor selected) and the location where mirror 310 is pointed. Position sensor 3166 is provided to directly measure the position of the drive

shaft (not shown) of galvanometer motor 3164. The output of position sensor 3166 is differentiated at differentiator 3168 to provide the velocity of the drive shaft of motor 3164. This velocity is summed with the error from eye movement sensor 100. The sum is integrated at integrator 3160 and input to current amplifier 3162 to drive galvanometer motor 3164. As the drive shaft of motor 3164 rotates mirror 310, the error that eye movement sensor 100 measures decreases to a negligible amount. The velocity feedback via position sensor 3166 and differentiator 3168 provides servo controller/motor driver 316 with the ability to react quickly when the measured sensor error is large.

Light energy reflected from eye 10, as designated by reference numeral 101-R, travels back through optics 300 and beamsplitter 200 for detection at sensor 100. Sensor 100 determines the amount of eye movement based on the changes in reflection energy 101-R. Error control signals indicative of the amount of eye movement are fed back by sensor 100 to beam angle adjustment mirror optics 300. The error control signals govern the movement or realignment of mirrors 310 and 320 in an effort to drive the error control signals to zero. In doing this, light energy 101-T and beam 502 are moved in correspondence with eye movement while the actual position of beam 502 relative to the center of the pupil is controlled by X-Y translation mirror optics 520.

In order to take advantage of the properties of beamsplitter 200, light energy 101-T must be of a different wavelength than that of treatment laser beam 502. The light energy should preferably lie outside the visible spectrum so as not to interfere or obstruct a surgeon's view of eye 10. Further, if the

present invention is to be used in ophthalmic surgical procedures, light energy 101-T must be "eye safe" as defined by the American National Standards Institute (ANSI). While a variety of light wavelengths satisfy the above requirements, by way of example, light energy 101-T is infrared light energy in the 900 nanometer wavelength region. Light in this region meets the above noted criteria and is further produced by readily available, economically affordable light sources. One such light source is a high pulse repetition rate GaAs 905 nanometer laser operating at 4 kHz which produces an ANSI defined eye safe pulse of 10 nanojoules in a 50 nanosecond pulse.

A preferred embodiment method for determining the amount of eye movement, as well as eye movement sensor 100 for carrying out such a method, are described in detail in the aforementioned copending patent application. However, for purpose of a complete description, sensor 100 will be described briefly with the aid of the block diagram shown in FIG. 2. Sensor 100 may be broken down into a delivery portion and a receiving portion. Essentially, the delivery portion projects light energy 101-T in the form of light spots 21, 22, 23 and 24 onto a boundary (e.g., iris/pupil boundary 14) on the surface of eye 10. The receiving portion monitors light energy 101-R in the form of reflections caused by light spots 21, 22, 23 and 24.

In delivery, spots 21 and 23 are focused and positioned on axis 25 while spots 22 and 24 are focused and positioned on axis 26 as shown. Axes 25 and 26 are orthogonal to one another. Spots 21, 22, 23 and 24 are focused to be incident on and evenly spaced about iris/pupil boundary 14. The four spots 21, 22, 23 and 24 are of equal energy and are spaced

evenly about and on iris/pupil boundary 14. This placement provides for two-axis motion sensing in the following manner. Each light spot 21, 22, 23 and 24 causes a certain amount of reflection at its position on iris/pupil boundary 14. Since boundary 14 moves in coincidence with eye movement, the amount of reflection from light spots 21, 22, 23 and 24 changes in accordance with eye movement. By spacing the four spots evenly about the circular boundary geometry, horizontal or vertical eye movement is detected by changes in the amount of reflection from adjacent pairs of spots. For example, horizontal eye movement is monitored by comparing the combined reflection from light spots 21 and 24 with the combined reflection from light spots 22 and 23. In a similar fashion, vertical eye movement is monitored by comparing the combined reflection from light spots 21 and 22 with the combined reflection from light spots 23 and 24.

More specifically, the delivery portion includes a 905 nanometer pulsed diode laser 102 transmitting light through optical fiber 104 to an optical fiber assembly 105 that splits and delays each pulse from laser 102 into preferably four equal energy pulses. Assembly 105 includes one-to-four optical splitter 106 that outputs four pulses of equal energy into optical fibers 108, 110, 112, 114. In order to use a single processor to process the reflections caused by each pulse transmitted by fibers 108, 110, 112 and 114, each pulse is uniquely delayed by a respective fiber optic delay line 109, 111, 113 and 115. For example, delay line 109 causes a delay of zero, i.e., DELAY=0x where x is the delay increment; delay line 111 causes a delay of x, i.e., DELAY=1x; etc.

The pulse repetition frequency and delay increment x are chosen so that the data rate of sensor

100 is greater than the speed of the movement of interest. In terms of saccadic eye movement, the data rate of sensor 100 must be on the order of at least several hundred hertz. For example, a sensor data rate of approximately 4 kHz is achieved by 1) selecting a small but sufficient value for x to allow processor 160 to handle the data (e.g., 160 nanoseconds), and 2) selecting the time between pulses from laser 102 to be 250 microseconds (i.e., laser 102 is pulsed at a 4 kHz rate).

The four equal energy pulses exit assembly 105 via optical fibers 116, 118, 120 and 122 which are configured as a fiber optic bundle 123. Bundle 123 arranges the optical fibers such that the center of each fiber forms the corner of a square. Light from assembly 105 is passed through an optical polarizer 124 that outputs horizontally polarized light beams as indicated by arrow 126. Horizontally polarized light beams 126 pass to focusing optics 130 where spacing between beams 126 is adjusted based on the boundary of interest. Additionally, a zoom capability (not shown) can be provided to allow for adjustment of the size of the pattern formed by spots 21, 22, 23 and 24. This capability allows sensor 100 to adapt to different patients, boundaries, etc.

A polarizing beam splitting cube 140 receives horizontally polarized light beams 126 from focusing optics 130. Cube 140 is configured to transmit horizontal polarization and reflect vertical polarization. Accordingly, cube 140 transmits only horizontally polarized light beams 126 as indicated by arrow 142. Thus, it is only horizontally polarized light that is incident on eye 10 as spots 21, 22, 23 and 24. Upon reflection from eye 10, the light energy is depolarized (i.e., it has both horizontal and

vertical polarization components) as indicated by crossed arrows 150.

The receiving portion first directs the vertical component of the reflected light as indicated by arrow 152. Thus, cube 140 serves to separate the transmitted light energy from the reflected light energy for accurate measurement. The vertically polarized portion of the reflection from spots 21, 22, 23 and 24, is passed through focusing lens 154 for imaging onto an infrared detector 156. Detector 156 passes its signal to a multiplexing peak detecting circuit 158 which is essentially a plurality of peak sample and hold circuits, a variety of which are well known in the art. Circuit 158 is configured to sample (and hold the peak value from) detector 156 in accordance with the pulse repetition frequency of laser 102 and the delay x. For example, if the pulse repetition frequency of laser 102 is 4 kHz, circuit 158 gathers reflections from spots 21, 22, 23 and 24 every 250 microseconds.

The values associated with the reflected energy for each group of four spots (i.e., each pulse of laser 102) are passed to a processor 160 where horizontal and vertical components of eye movement are determined. For example let $R_{21}$, $R_{22}$, $R_{23}$ and $R_{24}$ represent the detected amount of reflection from one group of spots 21, 22, 23 and 24, respectively. A quantitative amount of horizontal movement is determined directly from the normalized relationship

$$\frac{(R_{21}+R_{24})-(R_{22}+R_{23})}{R_{21}+R_{22}+R_{23}+R_{24}} \qquad (1)$$

while a quantitative amount of vertical movement is determined directly from the normalized relationship Note that normalizing (i.e., dividing by $R_{21}$ + $R_{22}$ + $R_{23}$

$$\frac{(R_{21}+R_{22})-(R_{23}+R_{24})}{R_{21}+R_{22}+R_{23}+R_{24}} \qquad (2)$$

$+ R_{24})$ reduces the effects of variations in signal strength. Once determined, the measured amounts of eye movement are sent to beam angle adjustment mirror optics 300.

The advantages of the present invention are numerous. Eye movement is measured quantitatively and used to automatically redirect both the laser delivery and eye tracking portions of the system independent of the laser positioning mechanism. The system operates without interfering with the particular treatment laser or the surgeon performing the eye treatment procedure.

Although the invention has been described relative to a specific embodiment thereof, there are numerous variations and modifications that will be readily apparent to those skilled in the art in the light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

Claims:

1. A laser beam delivery and tracking system for eroding a surface, comprising:

laser means for generating laser light along an original beam path at an energy level suitable for eroding said surface in accordance with a specified pattern;

an optical translator for shifting said original beam path onto a resulting beam path that is parallel to said original beam path;

an optical angle adjuster for changing said original beam path's angle relative to said original beam path, wherein said laser light is incident on said surface; and

a sensor for detecting measurable amounts of movement of said surface relative to said optical axis and for generating error control signals indicative of said measurable amounts of movement, said optical angle adjuster responding to said error control signals to change said resulting beam path's angle.

2. A system as in claim 1 wherein said optical translator includes at least two mirrors capable of independent translational movement for shifting said original beam path along two axes that are orthogonal to one another.

3. A system as in claim 1 wherein said optical angle adjuster includes at least two mirrors capable of independent rotational movement for changing said resulting beam path's angle along two axes that are orthogonal to one another.

4. A system as in claim 1 wherein said sensor comprises:

a light source for generating light energy that is non-eroding with respect to said surface, said light energy traveling on a delivery light path;

an optical delivery arrangement for delivering said light energy on said delivery light path to said optical angle adjuster, said delivery light path's angle changing in correspondence with said optical angle adjuster, wherein said light energy is ultimately incident on said surface and wherein a portion of said light energy is reflected from said surface as reflected energy traveling on a reflected light path back through said optical angle adjuster; and

an optical receiving arrangement for detecting said reflected energy from said optical angle adjuster and for generating said error control signals based on said reflected energy.

5. A system as in claim 4 further comprising a dichroic beamsplitter optically interposed between said sensor, said optical translator and said optical angle adjuster for directing said light energy to said optical angle adjuster, directing said reflected light energy to said sensor, and directing said resulting beam path to said optical angle adjuster.

6. A method of laser beam delivery and tracking for eroding a surface, comprising the steps of:

focusing a generated arrangement of light beams to be incident on an optical beam path adjuster, each beam of said generated arrangement being of an energy level that is non-eroding with respect to said surface;

focusing a laser light beam to be incident on said optical beam path adjuster in a parallel relationship with said generated arrangement, said laser light beam being of an energy level that is suitable to erode said surface;

operating said optical beam path adjuster to cause said generated arrangement and said laser light beam to be incident on said surface in said parallel relationship, wherein a portion of each said beam of said generated arrangement reflects from said surface as a reflected beam that is part of a reflected arrangement of light beams corresponding to said generated arrangement, said reflected arrangement having an energy level indicative of movement of said surface; and

realigning said optical beam path adjuster based on said energy level of said reflected arrangement to simultaneously move said generated arrangement and said laser light beam in said parallel relationship in correspondence with said movement of said surface.

7. A method according to claim 6 wherein said steps of operating and realigning comprise the step of altering beam angles of each said beam of said generated arrangement and said laser light beam along two axes that are orthogonal to one another.

8. A method according to claim 7 wherein beam angles along each of said two axes are altered independently.

9. An eye treatment laser beam delivery and eye tracking system for treating the surface of an eye, comprising:

laser means for generating laser light along a original beam path at an energy level suitable for treating said eye;

an optical translator for shifting said original beam path onto a resulting beam path;

an optical angle adjuster for changing said resulting beam path's angle relative to an optical axis of said eye, wherein said laser light is incident on said eye;

an eye movement sensor for detecting measurable amounts of movement of said eye relative to said optical axis and for generating error control signals indicative of said measurable amounts of movement;

said eye movement sensor including 1) a light source for generating light energy that is non-damaging with respect to said eye, 2) an optical delivery arrangement for delivering said light energy on a delivery light path to said optical angle adjuster in a parallel relationship with said resulting beam path, said delivery light path's angle changed by said optical angle adjuster in correspondence with said resulting beam path's angle, wherein said light energy and said laser light are incident on said eye in said parallel relationship, wherein a portion of said light

energy is reflected from said eye as reflected energy traveling on a reflected light path back through said optical angle adjuster, and 3) an optical receiving arrangement for detecting said reflected energy from said optical angle adjuster and for generating said error control signals based on said reflected energy wherein said optical angle adjuster is responsive to said error control signals for changing said resulting beam path's angle and said delivery light path's angle in correspondence with one another.

10. A system as in claim 9 wherein said laser means is a 193 nanometer wavelength excimer laser whose energy level is suitable for ablating away corneal tissue of said eye in a photo decomposition process.

11. A system as in claim 9 wherein said optical translator includes at least two mirrors capable of independent translational movement for shifting said original beam path along two axes that are orthogonal to one another.

12. A system as in claim 9 wherein said optical angle adjuster includes at least two mirrors capable of independent rotational movement for changing said resulting beam path's angle and said delivery light path's angle along two axes that are orthogonal to one

another.

13. A system as in claim 9 wherein said light source generates said light energy with a wavelength outside the visible spectrum.

14. A system as in claim 10 wherein said light source generates said light energy with a wavelength of approximately 900 nanometers.

15. A system as in claim 14 further comprising a dichroic beamsplitter optically interposed between said eye movement sensor, said optical translator and said optical angle adjuster for directing said light energy to said optical angle adjuster, directing said reflected light energy to said eye movement sensor, and directing said resulting beam path to said optical angle adjuster.

16. A system as in claim 9 wherein said optical delivery arrangement includes:

an optical splitter for converting said light energy into a plurality of light spots; and

focusing optics for focusing said plurality of light spots through said optical angle adjuster to direct said plurality of light spots incident on a corresponding plurality of positions located on a

boundary whose movement is coincident with that of said movement of said eye, said boundary defined by two visually adjoining surfaces having different coefficients of reflection, wherein a portion of said reflected energy is reflected from each of said plurality of positions.

17. A system as in claim 16 wherein said boundary is circular and said plurality of light spots comprises four light spots, said focusing optics including means for spacing said four light spots approximately evenly about said circular boundary.

18. A system as in claim 17 wherein said circular boundary is disposed around the center of the pupil of said eye.

19. A system as in claim 18 wherein said circular boundary is naturally occurring on the surface of said eye.

20. A system as in claim 18 wherein each of said plurality of light spots is outside the visible spectrum.

21. A system as in claim 16 wherein said laser means is a 193 nanometer wavelength excimer laser whose

energy level is suitable for ablating away corneal tissue of said eye in a photo decomposition process, and wherein each of said plurality of light spots has a wavelength of approximately 900 nanometers.

22. A system as in claim 21 further comprising a dichroic beamsplitter optically interposed between said eye movement sensor, said optical translator and said optical angle adjuster for transmission of said plurality of light spots to said optical angle adjuster, transmission of said reflected light energy to said eye movement sensor, and reflection of said resulting beam path to said optical angle adjuster.

23. A system as in claim 16 wherein said optical delivery arrangement further includes:

means for polarizing each of said plurality of light spots into horizontally polarized components; and

a polarization beam splitting cube for transmitting only said horizontally polarized components of each of said plurality of light spots to said optical angle adjuster.

24. A system as in claim 23 wherein said reflected energy is vertically and horizontally polarized, said optical receiving arrangement including:

said polarization beam splitting cube for directing said reflected energy that is vertically polarized separately from said reflected energy that is horizontally polarized;

energy detecting optics for measuring said reflected energy that is vertically polarized; and

a processor for determining said measurable amounts of said movement of said eye based on said reflected energy that is vertically polarized.

25. A laser beam delivery and tracking system for eye treatment, comprising:

a laser for generating laser light along an original beam path at an energy level suitable for eye treatment;

a mechanism for shifting said original beam path onto a different beam path from said original beam path; and

a sensor for detecting measurable amounts of movement of said eye and for generating control signals indicative of said measurable amounts of movement, said mechanism responding to said control signals to change said beam path to said different beam paths.

26. A laser beam delivery and tracking system for eroding a surface, comprising:

a laser for generating laser light along an original beam path at an energy level suitable for eroding said surface;

a mechanism for shifting said original beam path onto a different beam path in accordance with a specified pattern results in a shape change to said surface;

a sensor for detecting measurable amounts of movement of said surface and for generating a control signal indicative of said measurable amounts of movement, and

a separate adjustment mechanism for changing said beam path in response to said control signal wherein said laser light beam is corrected to achieve said specified pattern.

27. The method of changing optical properties of an eye by operating upon the cornea of the eye, which method comprises selective ultravoilet irradiation and attendant ablative photodecomposition of the cornea is a volumetric removal of corneal tissue and with depth penetration into the stroma and to a predetermined curvature profile where the method includes sensing eye position and adjusting said ultravoilet irratiation to assure said predetermined curvature

profile is achieved.

28. A method of eroding an object to a desired shape, comprising the steps of:

producing a plurality of laser beam shots;

selecting a shot pattern for said plurality of laser beam shots wherein said shot pattern is capable of eroding a said object to a desired shape;

applying said plurality of laser beam shots to said object in a spatially distributed pattern spread over an area of said object to be eroded so that sequential shots are spaced a sufficient distance from one another so that eroded material will not interfere with the subsequent shot; and

repeating said laser beam shots until the cumulative shots fill in and complete said pattern to achieve said desired shape.

29. A system for eroding an object to a desired shape comprising:

a pulsed laser for producing a plurality of laser beam shots, each of said plurality of laser beam shots traveling on an original beam path;

a mechanism for shifting said original beam path onto a different beam path to said original beam path in accordance with a predetermined shot pattern, wherein said plurality of said laser beam shots are

directed to said object to be eroded; and

a controller for issuing shift control commands to said mechanism in accordance with said predetermined shot pattern, wherein said shot pattern is capable of eroding said object to said desired shape, said controller issuing shift control commands to apply said plurality of laser beam shots to said object in a spatially distributed pattern spread over the area of said object to be eroded so that said laser beam shots are sequentially spaced from one another on said object a sufficient distance to allow eroded material from a previous shot to dissipate prior to a subsequent adjacent shot being made with cumulative shots filling in and completing said predetermined shot pattern to achieve said desired shape.

30. A method of ablating an article to a specific shape comprising:

providing an article to be shaped;

providing the volume and shape of material to be ablated from said article;

providing a pulse ablater beam with a pulse repetition rate to abrade a microvolume of material from said article;

providing a location pattern of overlapping but not coaxial location for said beam to ablate material;

providing a pulse sequencing program for said beam

where said successive ablation pulses are spaced from one another by at least as far as one beam width and sufficiently close to enable the beam to be moved to the successive location within the time of the pulse repetition rate; and

ablating material from said article in accordance with said pattern in a sequence until said specific shape is achieved.

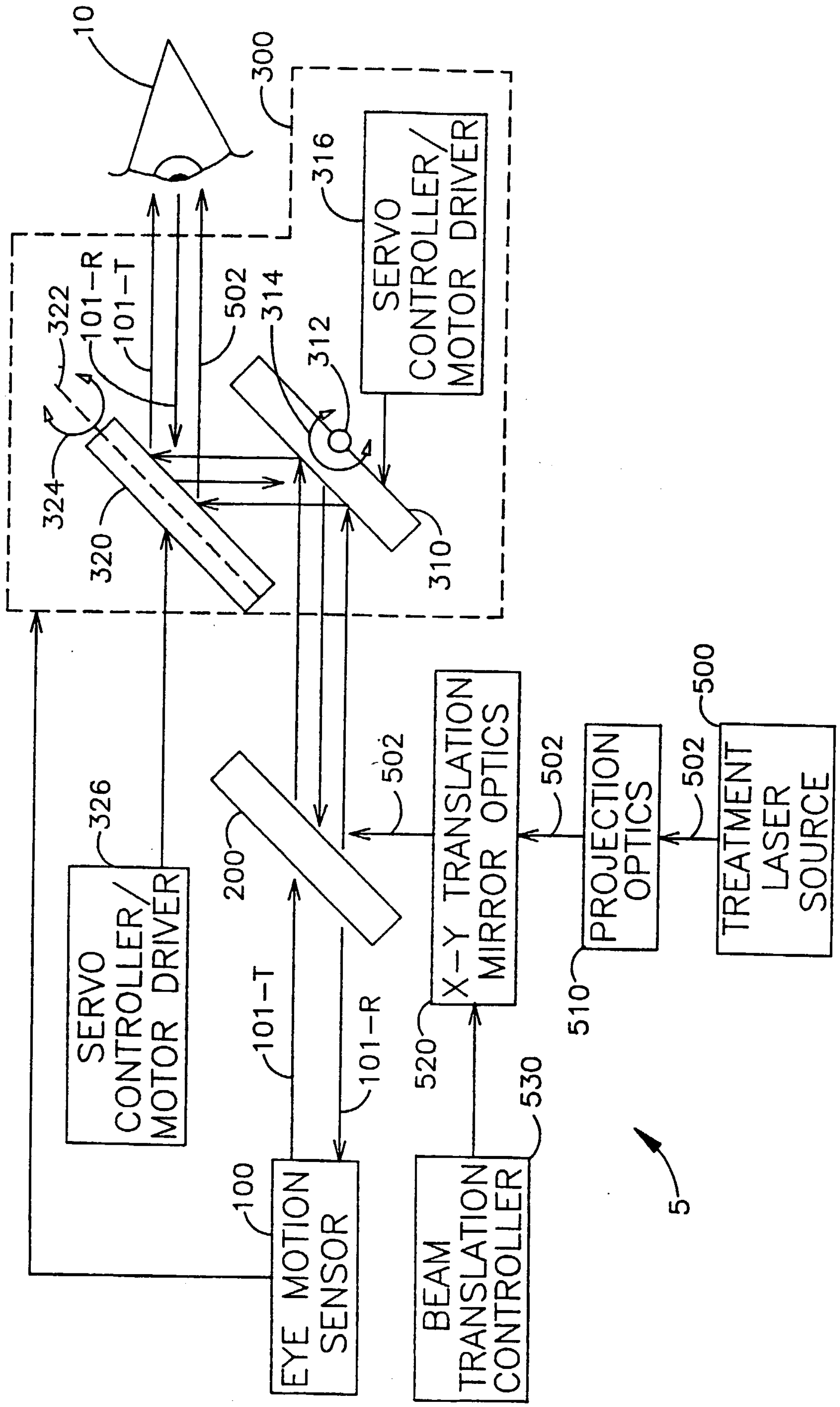
10
300
316
SERVO CONTROLLER/ MOTOR DRIVER
322
101-R
101-T
502
314
312
324
320
310
326
SERVO CONTROLLER/ MOTOR DRIVER
200
502
X-Y TRANSLATION MIRROR OPTICS
502
PROJECTION OPTICS
502
500
TREATMENT LASER SOURCE
510
520
530
101-T
101-R
100
EYE MOTION SENSOR
BEAM TRANSLATION CONTROLLER
5

FIG. 1

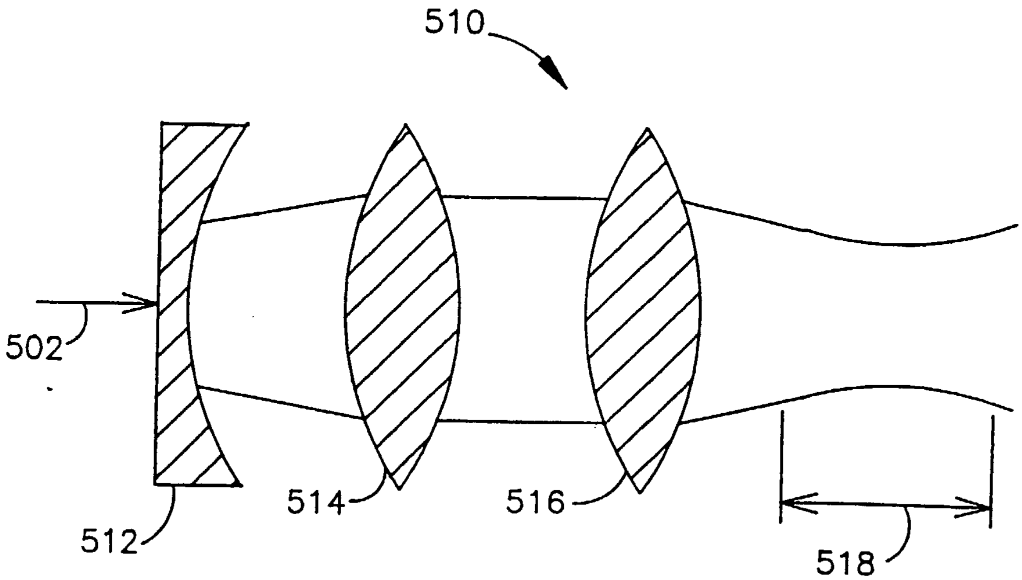
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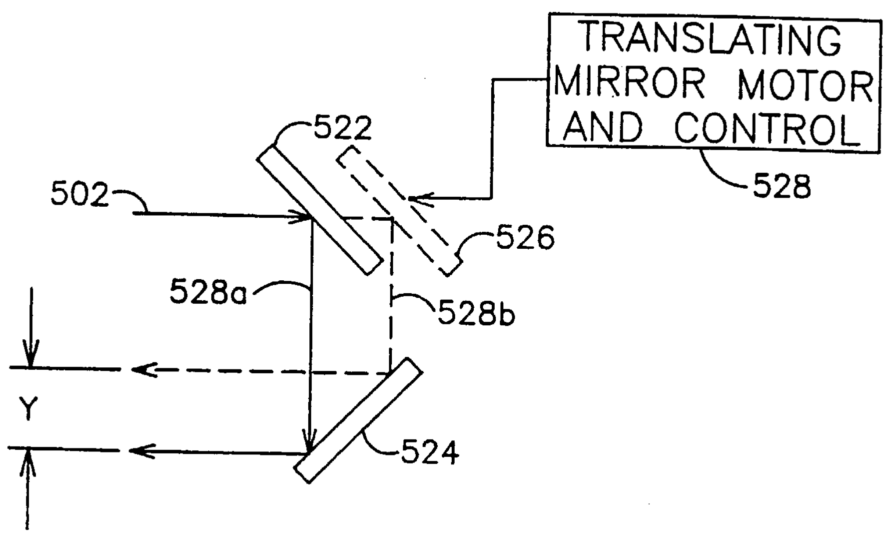
*FIG. 2*


TRANSLATING
MIRROR MOTOR
AND CONTROL
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522
502
526
528a
528b
Y
524

*FIG. 3*

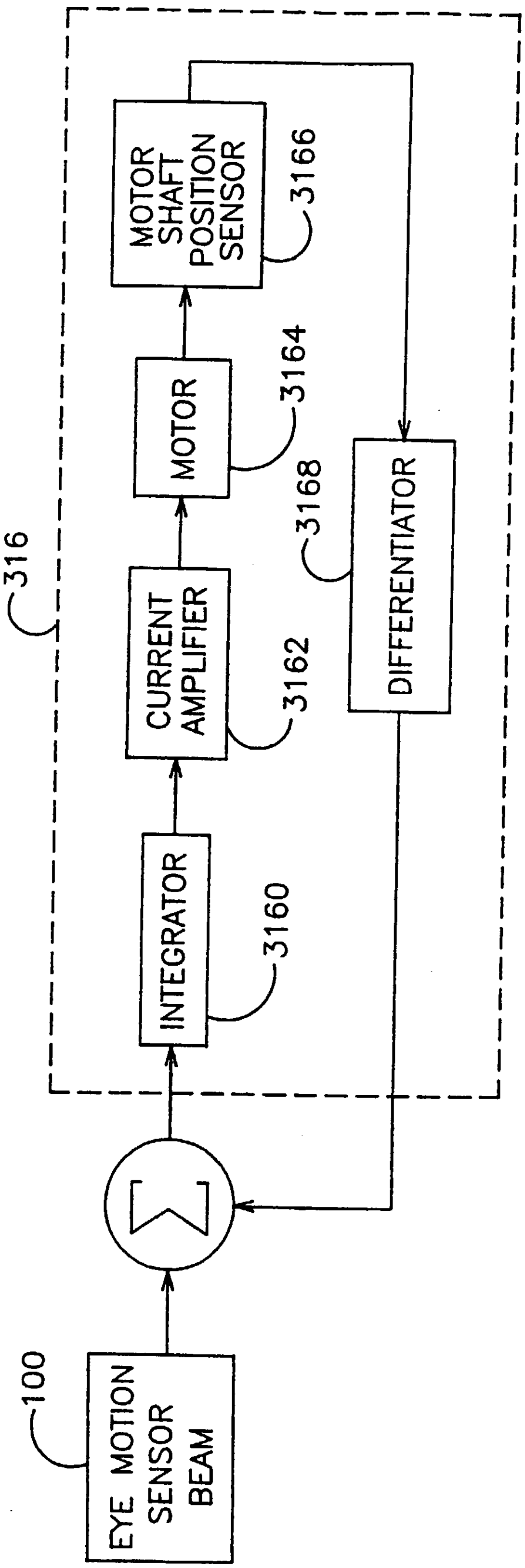
316
MOTOR SHAFT POSITION SENSOR
3166
MOTOR
3164
3168
DIFFERENTIATOR
CURRENT AMPLIFIER
3162
INTEGRATOR
3160
100
EYE MOTION SENSOR BEAM

FIG. 4

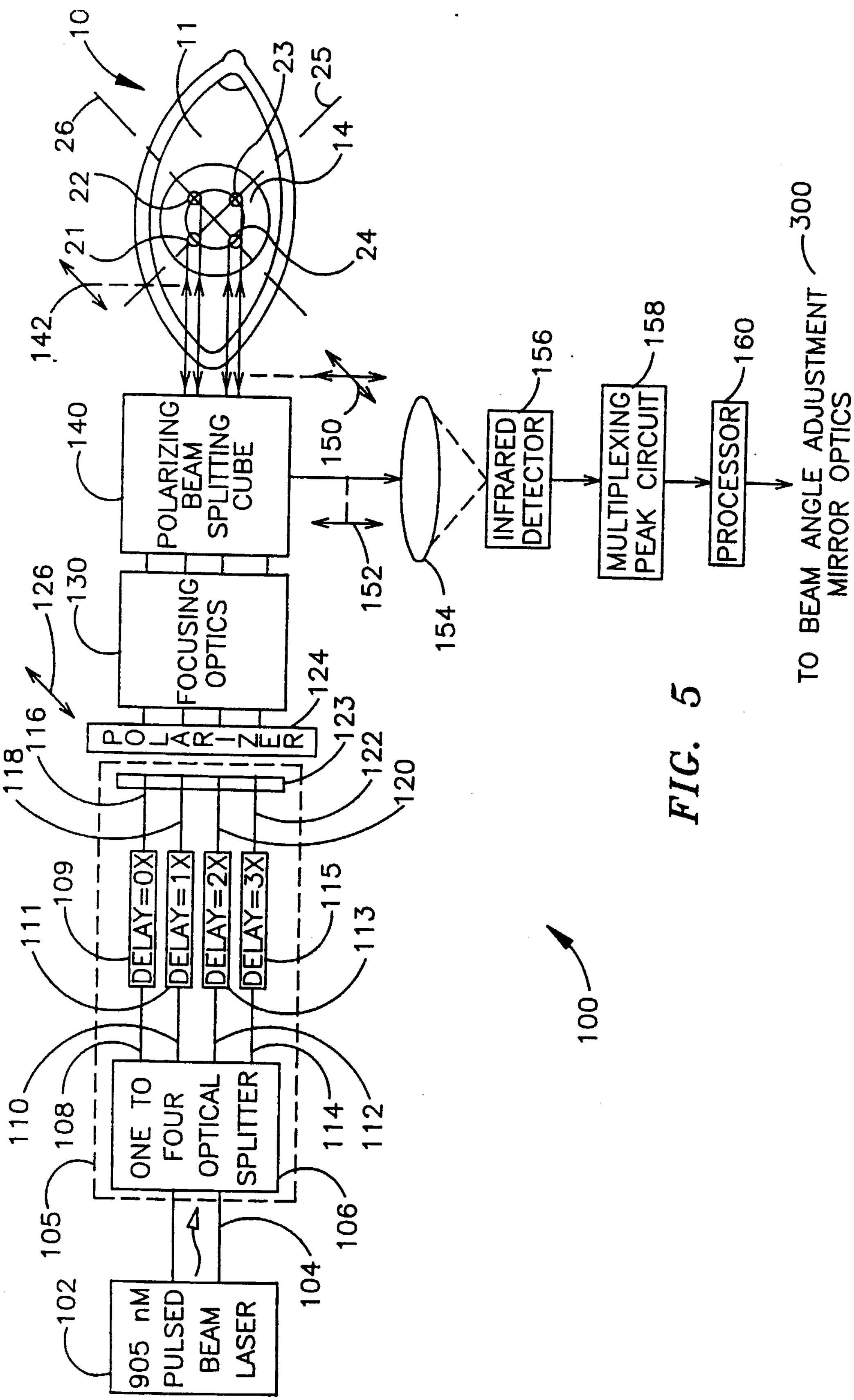
905 nM PULSED BEAM LASER
ONE TO FOUR OPTICAL SPLITTER
DELAY=0X
DELAY=1X
DELAY=2X
DELAY=3X
POLARIZER
FOCUSING OPTICS
POLARIZING BEAM SPLITTING CUBE
INFRARED DETECTOR
MULTIPLEXING PEAK CIRCUIT
PROCESSOR
TO BEAM ANGLE ADJUSTMENT MIRROR OPTICS
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FIG. 5

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC(6) :A61N 5/06
US CL :351/221; 606/4, 14
According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 351/201, 212, 214, 216, 221, 246; 606/2-18

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X<br>---<br>Y | WO, A, 87/06478 (BUYS ET AL.) 05 November 1987, see the entire document. | 28, 29<br>---<br>30 |
| Y | US, A, 4,069,823 (ISAKOV ET AL.) 24 January 1978, see the entire document. | 1-5, 9-26 |
| Y | US, A, 4,848,340 (BILLE ET AL.) 18 July 1989, see the entire document. | 1-27 |
| Y | US, A, 4,881,808 (BILLE ET AL.) 21 November 1989, see the entire document. | 3-24 |
| Y | US, A, 4,718,418 (L'ESPERANCE, JR.) 12 January 1988, see the entire document. | 10, 21, 22, 27, 30 |

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

| | |
|---|---|
| Date of the actual completion of the international search<br>01 JUNE 1995 | Date of mailing of the international search report<br>22 JUN 1995 |
| Name and mailing address of the ISA/US<br>Commissioner of Patents and Trademarks<br>Box PCT<br>Washington, D.C. 20231<br>Facsimile No. (703) 305-3230 | Authorized officer<br>DAVID SHAY Stacia Sinuik for<br>Telephone No. (703) 308-2215 |

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | US, A, 4,972,836 (SCHENCK ET AL.) 27 November 1990, see the entire document. | 14-20, 23, 24 |
| Y | US, A, 4,702,245 (SCHRODER ET AL.) 27 October 1987, see the entire document. | 23, 24 |